Antimatter Gravity Experiment at Fermilab

The AGE Collaboration

Duke University
Fermilab
First Point Scientific, Inc
Hbar Technologies, LLC
Illinois Institute of Technology
Kansas State University
Luther College
NASA
Southern Methodist University
University of Arizona
University of Michigan
University of Texas

Thomas Phillips
Duke University

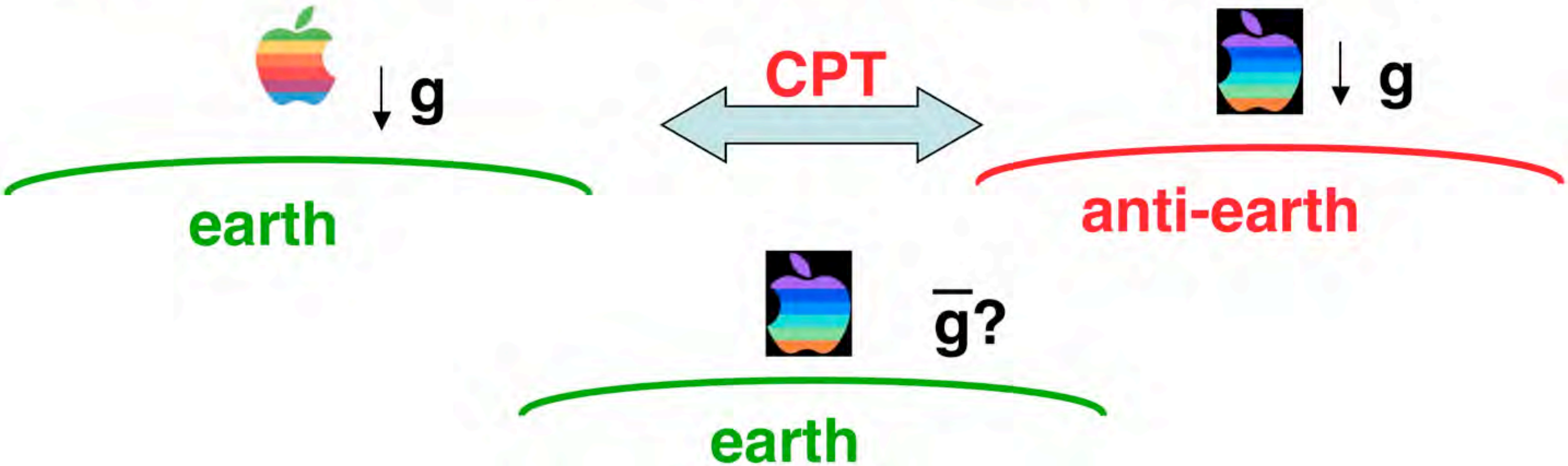
Outline

1. Motivation
2. Methods
   A. Preparing the antimatter
      a) catching antiprotons & positrons
      b) making an antihydrogen beam
   B. Transmission-grating interferometer
      - fast
      - $\Delta\bar{g}/g < 10^{-4}$ systematic limit
   C. Raman interferometer
      - $\Delta\bar{g}/g < 10^{-10}$ systematic limit
3. Status

Physics Motivation

$\bar{g}$ (the acceleration of antimatter towards the earth)

has never been directly measured!



CPT does not address how an antiapple falls on the earth.

General Relativity does predict that gravity is independent of composition, but all tests of GR to date have only been with matter-matter or matter-light interactions.

Possible hints that our understanding of gravity might be incomplete:

- General Relativity and Quantum Mechanics are fundamentally incompatible
- baryon asymmetry and dark energy natural if gravity is repulsive between matter & antimatter
- gravivector and graviscalar forces natural in quantum gravity (could cancel for matter-matter interactions but add for matter-antimatter interactions)

Ultimately a direct measurement is needed to settle the issue.

Antimatter Sources

To make antihydrogen, need

- antiprotons
  - 20×10^{10}/hour made at here
  - decelerate in main injector
  - capture in Penning trap
    - new deceleration ring planned
      - efficiency ~0.5
    - use degrader before ring is built
      - efficiency 10^{-4} with reverse linac
- Positrons
  - commercial solution available
  - uses solid neon, spoiled vacuum to moderate positrons from ^{22}Na source

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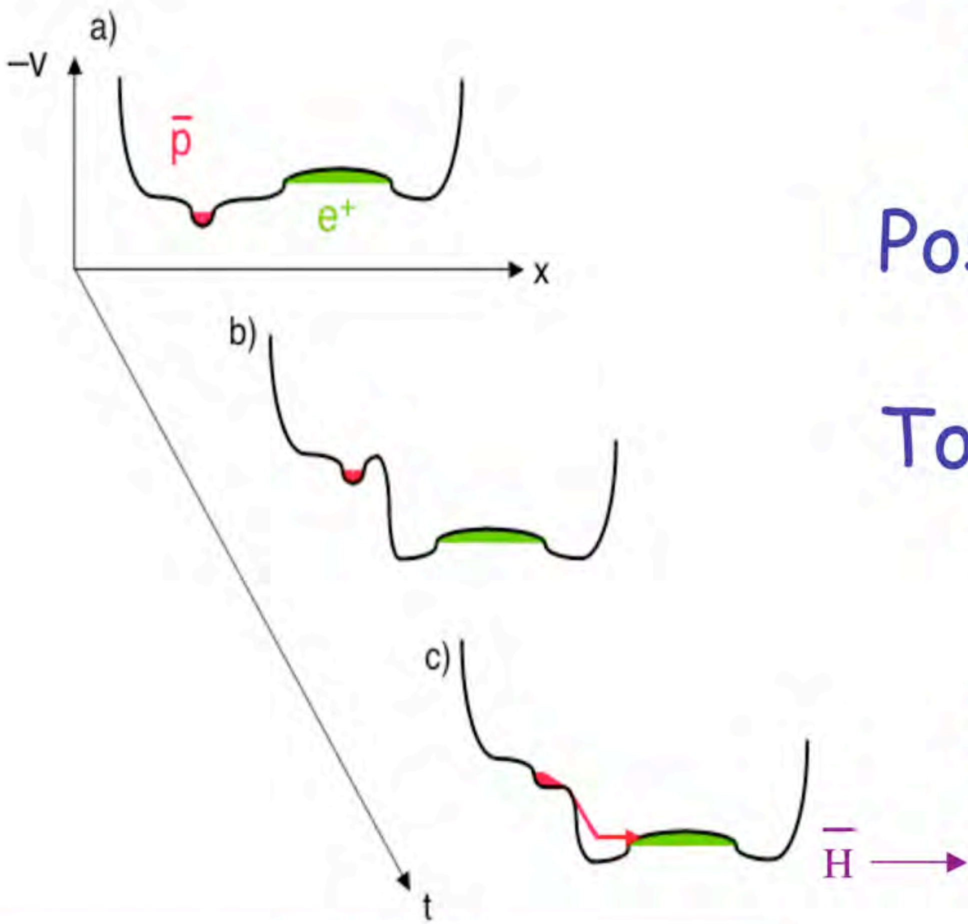
Making Antihydrogen

Antiprotons in trap are cooled with electrons

- ➢electrons cool to wall temp by synchrotron radiation

Positrons in a separate well



To make antihydrogen beam:

- ➢accelerate antiprotons thru positrons
- ➢some make antihydrogen and exit the trap in a beam
  - ➛high 1-pass conversion probability with achievable positron densities

Antihydrogen production efficiency:

ATHENA: (17±2)% Phys.Lett. B578 (2004) 32.

ATRAP: 11 % NIM 214 (2004) 22.

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A Neutral Beam Expt for Measuring $\bar{g}$

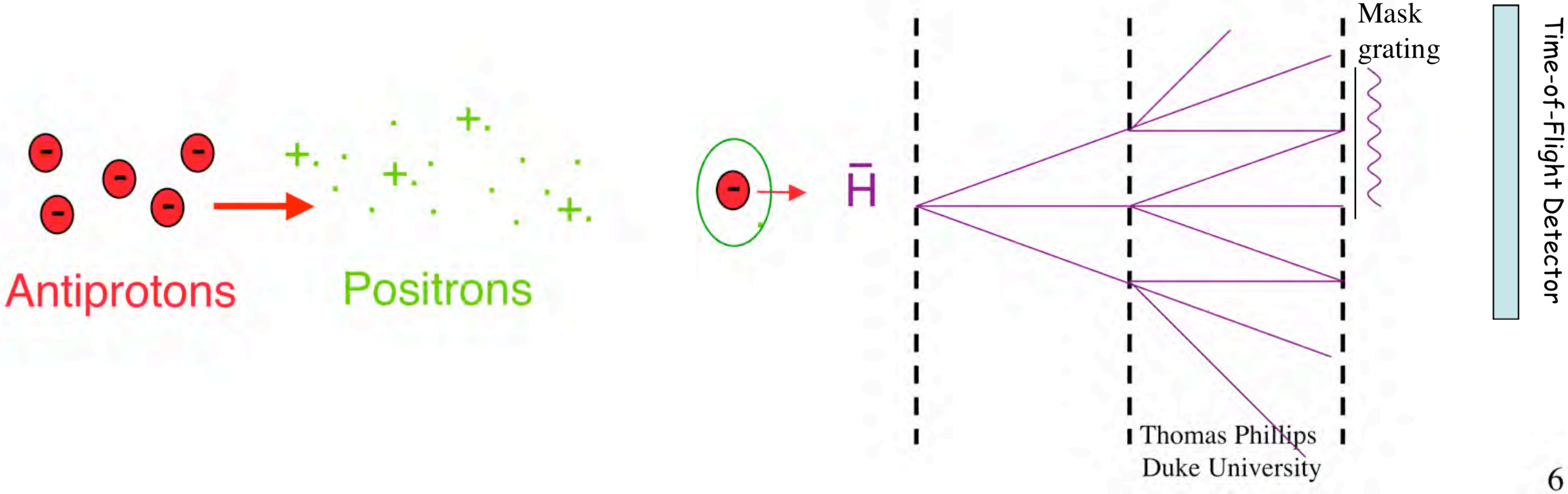
Make a low-velocity antihydrogen beam

Direct the beam through a transmission-grating interferometer

- Measure velocity with Time of Flight

Measure $\bar{g}$ by observing the gravitational phase shift

- Interference pattern shifts by the same amount the atoms "fall" as they traverse the interferometer



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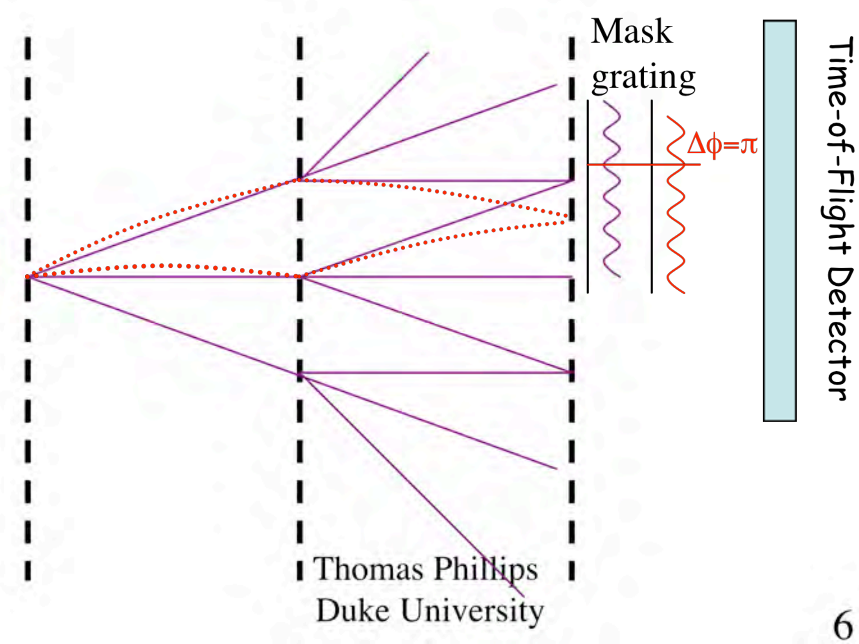
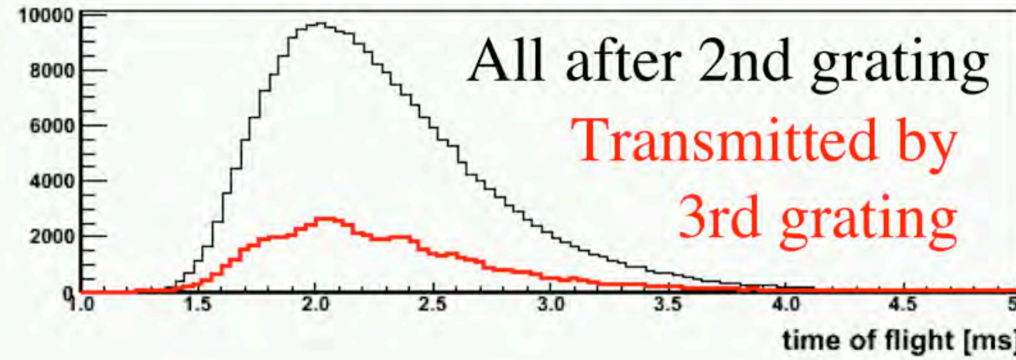


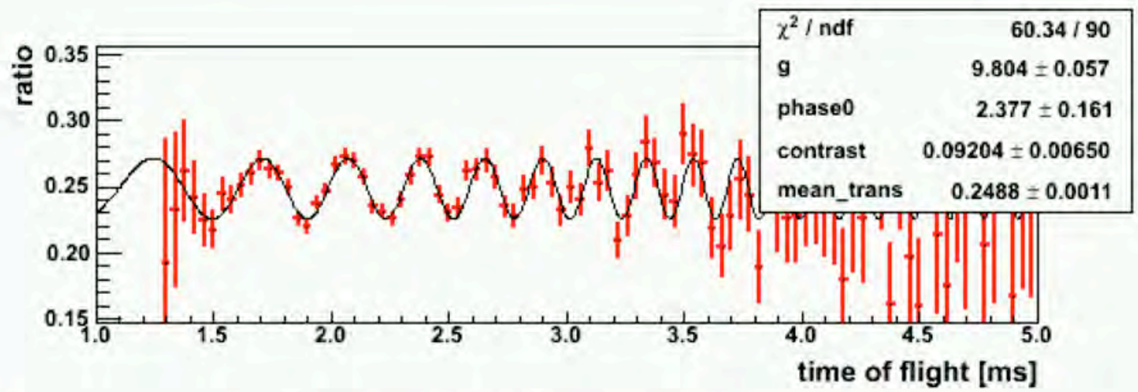
Monte Carlo Results

Simple MC shows what our data will look like.

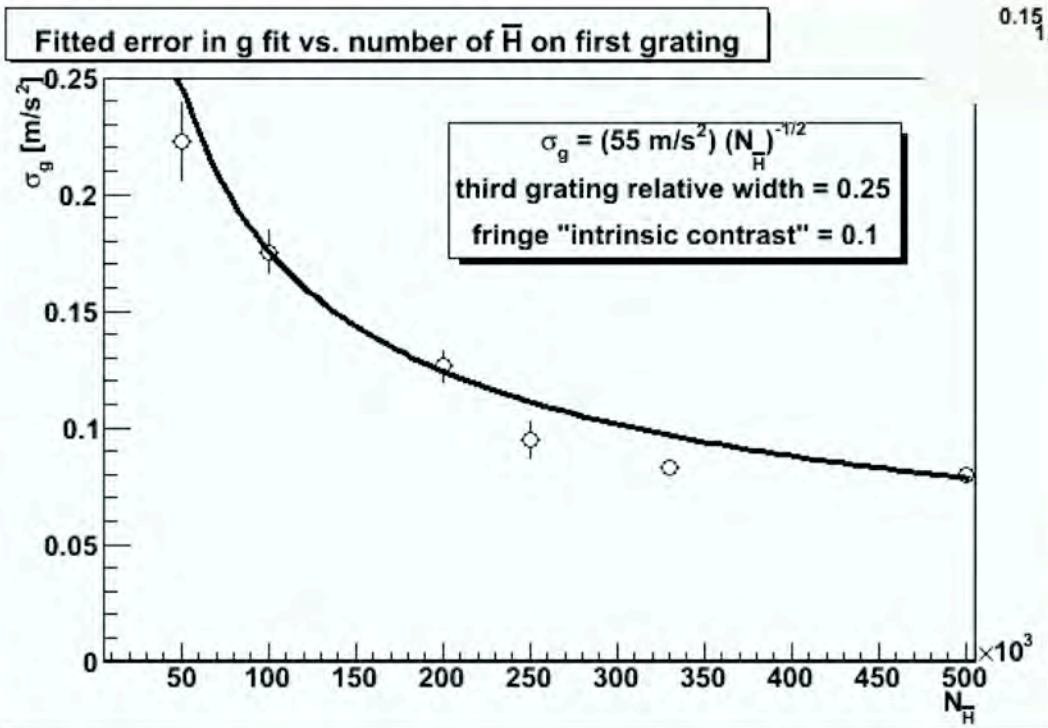
Phase shift is a function of time-of-flight: slower particles have larger gravitational phase shift

Get more transmission when interference peaks line up with gaps in mask





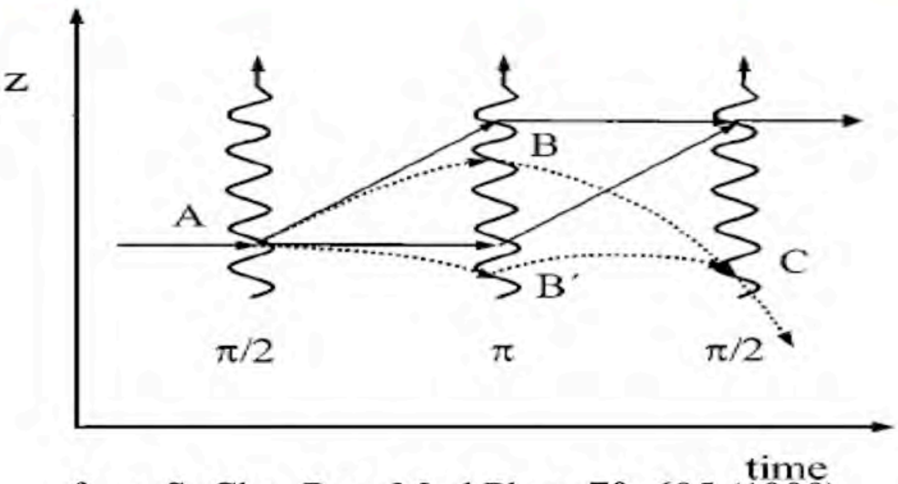
Time of Flight (msec)



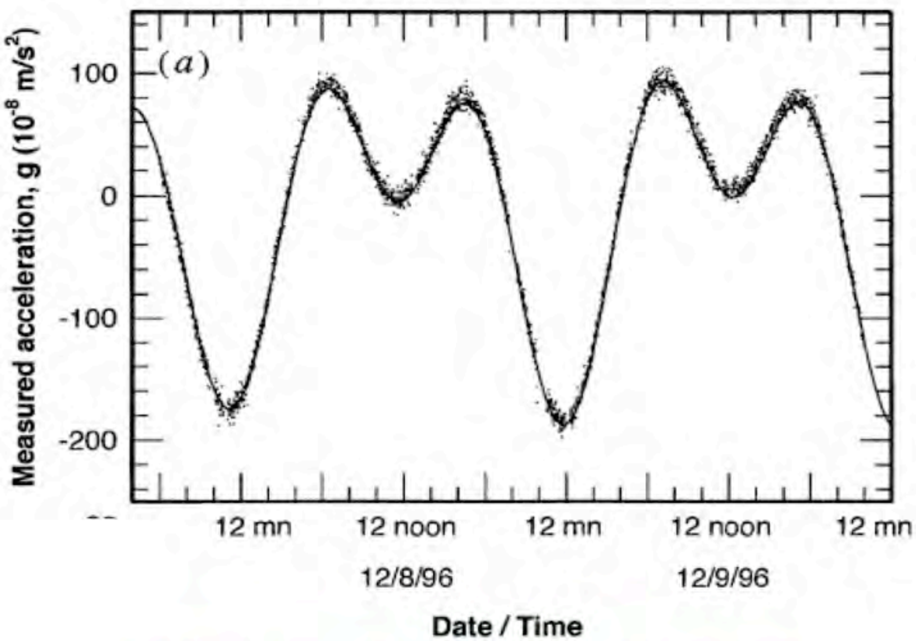
3.5 million antihydrogen will measure $\bar{g}$ to 0.1 m/s^2.

This corresponds to 3.5×10^8 trapped antiprotons with a 1% antihydrogen production efficiency:
1 day of antiproton production with degrader;
< 10 sec of antiproton production with decelerator ring

Raman Interferometer



from S. Chu, Rev. Mod.Phys. **70**, 685 (1998)



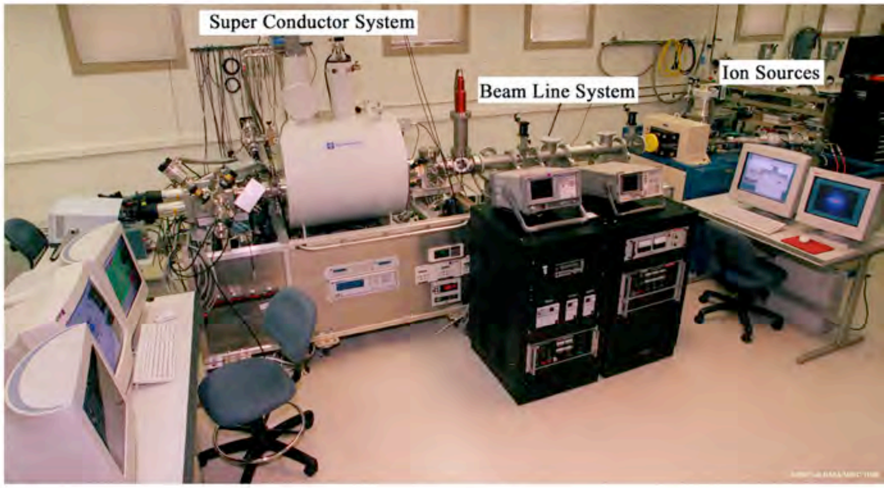
A. Peters *et al*. Philos. Trans. R. Soc. London Ser A **355,** 2223.

High-precision matter-antimatter difference measurement using Raman Interferometer

- split wave packet with laser
- reverse split with 2nd pulse
- recombine with 3rd pulse
- local g resolution 10^{-10} using Cs atoms
- hydrogen in development
  - 1000 trapped $\overline{H}$ for 2×10^{-7}
  - see Mark Raizen's talk
- can look for new ultra-weak forces by comparing H, $\overline{H}$

Status

- ➤Initial collaboration formed
  - ➢experts in
    - ➛accelerators & vacuum systems
    - ➛traps & positron plasmas
    - ➛interferometers
    - ➛atomic physics
- ➤Much of needed equipment is available
  - ➢HiPAT trap from NASA
    - ➛solenoid, trap, ion sources
  - ➢6T large-bore solenoid
  - ➢prototype interferometer



Funding Status

NSF proposals pending

- one to fund transmission-grating interferometer
  - includes antihydrogen beam
  - **could benefit from Fermilab endorsement!**
- one to fund trapping of hydrogen
  - Existing SGER and ARP (Texas) grants to get started

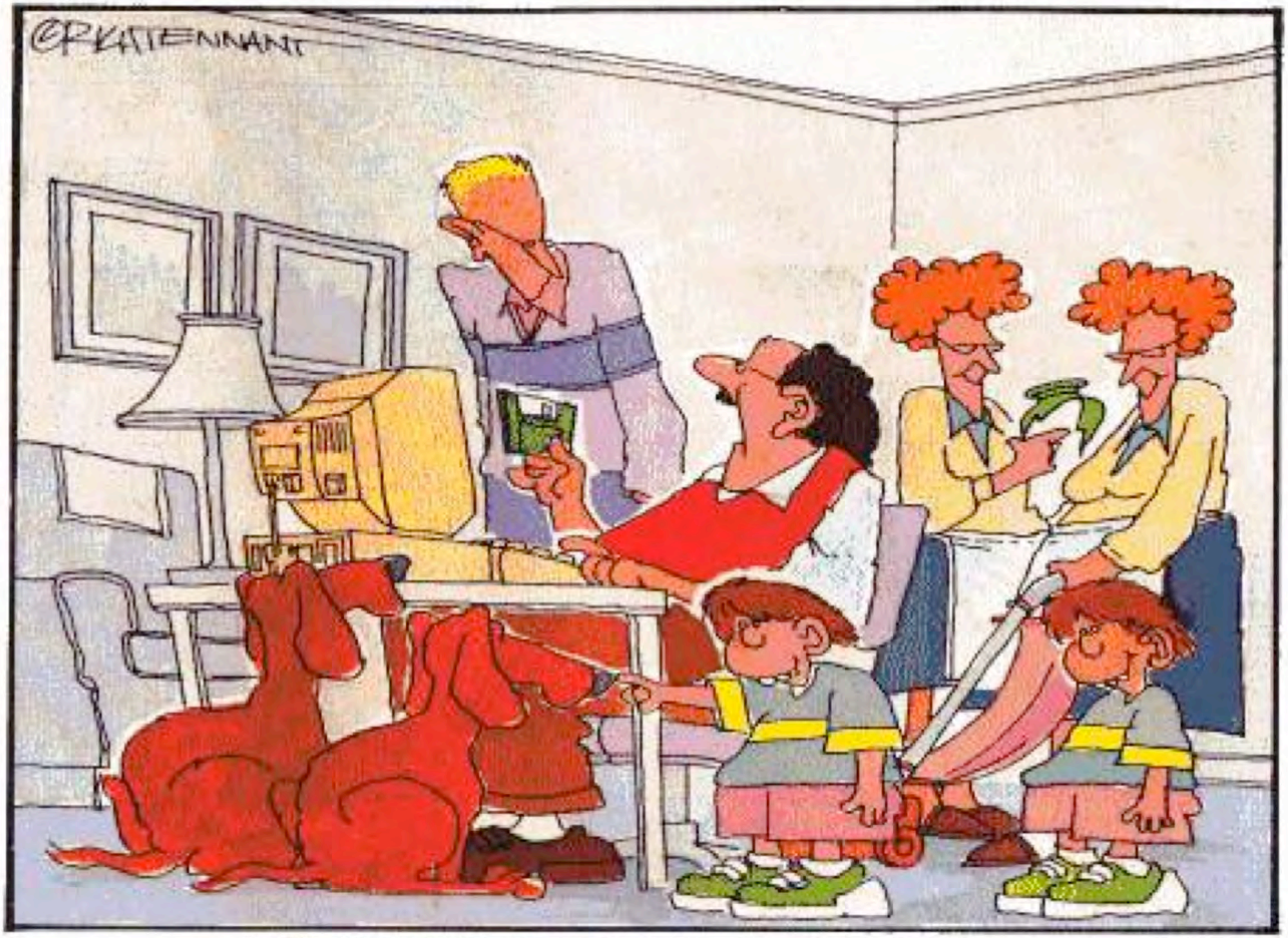
Private funding available for antiproton facility

- antiprotons to be used for medical treatments
- contingent on Fermilab approval
- business plan calls for building in 2009
  - need MI deceleration studies before plans can be finalized
- deceleration ring in 3rd year

Summary

- Fermilab has an opportunity to make the <u>first</u> direct measurement of antimatter gravity
  - potential to change our <u>view</u> of the universe!
  - Initial measurement soon after $\overline{H}$ production established.
    - Parasitic running is possible during Tevatron operations.
  - High precision attainable with Raman interferometer.
- External funding pending for both the experiment and the antiproton facility
  - A Fermilab endorsement could help with NSF funding.
- Great for Public Outreach!
  - The public loves antimatter, and this is an experiment that people can understand!

Backup



"I ALWAYS BACK UP EVERYTHING."

picture from http://comedy.glowport.com

"Do we already know the answer?"

Equivalence Principle limits

- graviscalar and gravivector interactions can cancel for matter-matter and add for matter-antimatter Nieto & Goldman Phys. Rep. 205, 221.

Virtual antimatter (Schiff argument) Schiff PRL 1, 254; Proc.Natl.Acad.Sci. 45, 69.

- non renomalizable as presented; too small to see (10^{-16}) when using contribution to stress-energy tensor Nieto & Goldman Phys. Rep. 205, 221.

K_S regenerated in K_L beam (Good argument) Good Phys. Rev. 121, 311.

- Argument requires absolute potentials
  - with relative potentials, too small to have been seen Nieto & Goldman Phys. Rep. 205, 221.
- CP violation in Kaon system from antigravity Chardin & Rax Phys. Lett. B 282, 256.

Energy not conserved (Morrison argument) Morrison Am.J.Phys. 26, 358.

- Depends upon coupling of photons to forces Nieto & Goldman Phys. Rep. 205, 221.
- Antigravity gives Hawking radiation from normal bodies Chardin AIP CP643, 385.

Neutrinos from SN1987a

- Some uncertainty that both ν and $\bar{\nu}$ observed.
- Insensitive to forces with ranges much less than 1 pc Nieto & Goldman Phys. Rep. 205, 221.

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In a word, "No". Antimatter gravity is an empirical question.

Only a direct measurement can provide a definitive answer!

Quantum Gravity

"a quantum-mechanically consistent construction of gravity requires a violation of the weak principle of equivalence" Nieto & Goldman, Phys.Rep. 205, 221 citing Kleinert Mod.Phys.Lett.A 4, 2329.

The spin-2 graviton generically has spin-1 (gravivector) and spin-0 (graviscalar) partners

- gravivector force is:
  - repulsive for matter-matter interactions
  - attractive for matter-antimatter interactions
- graviscalar force is always attractive
- gravivector and graviscalar forces can cancel for matter-earth and add for antimatter-earth:
  - e.g. $a \approx b$, $v \approx s$ in simplified potential below

$$V = -Gm_1m_2\left(1 \mp ae^{-r/v} + be^{-r/s}\right)/r$$

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Additional Motivation

The Antimatter Gravity Experiment will provide an excellent opportunity for graduate students

This program could be producing physics results between the Tevatron and Project X

Public Outreach!

The public loves antimatter!

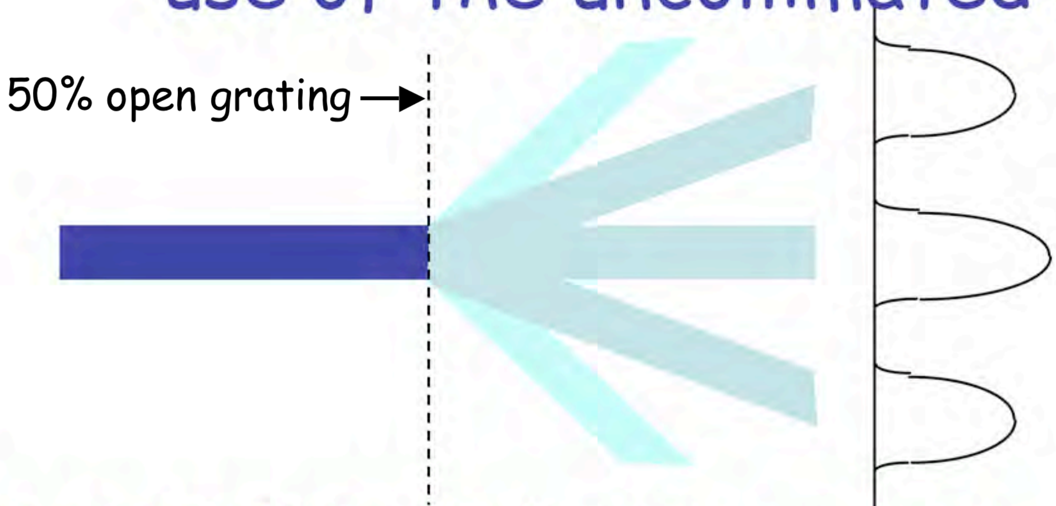
- CERN's press release announcing they had made antihydrogen generated the biggest response they had ever gotten.
- Latest example: Tom Hanks movie

The public can understand this experiment!

Particle physics needs good press!

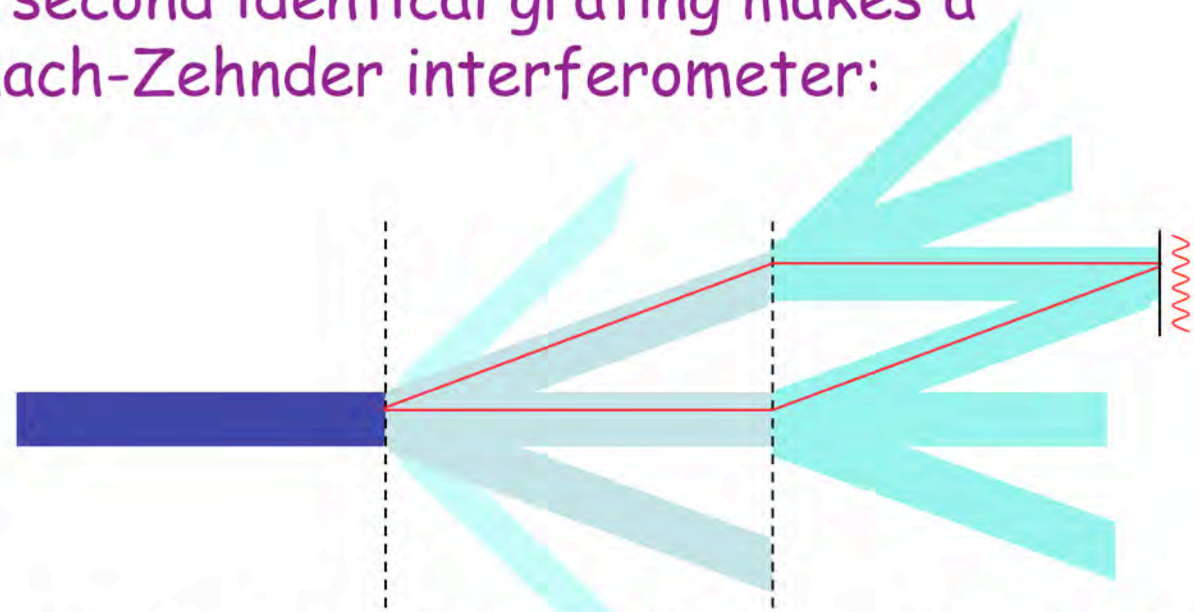
The Atomic Interferometer

This interferometer design can make efficient use of the uncollimated antihydrogen beam.



A single grating splits the beam and makes a diffration pattern.

A second identical grating makes a Mach-Zehnder interferometer:



The interference pattern has the same period as the gratings so a third identical grating can be used as a mask to analyze the phase of the pattern.
The gravitational phase shift will measure $\bar{g}$.

This is a "white-light" "extended source" interferometer

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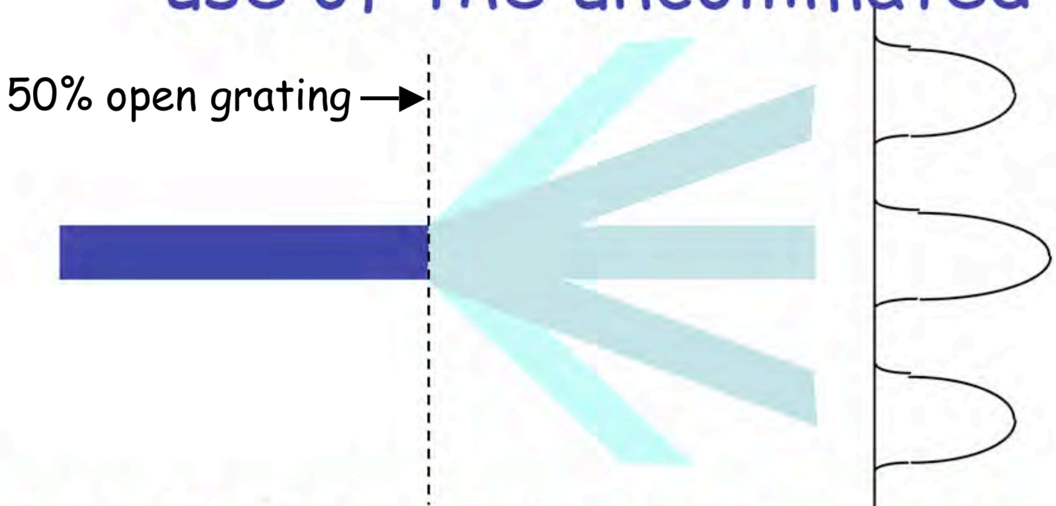

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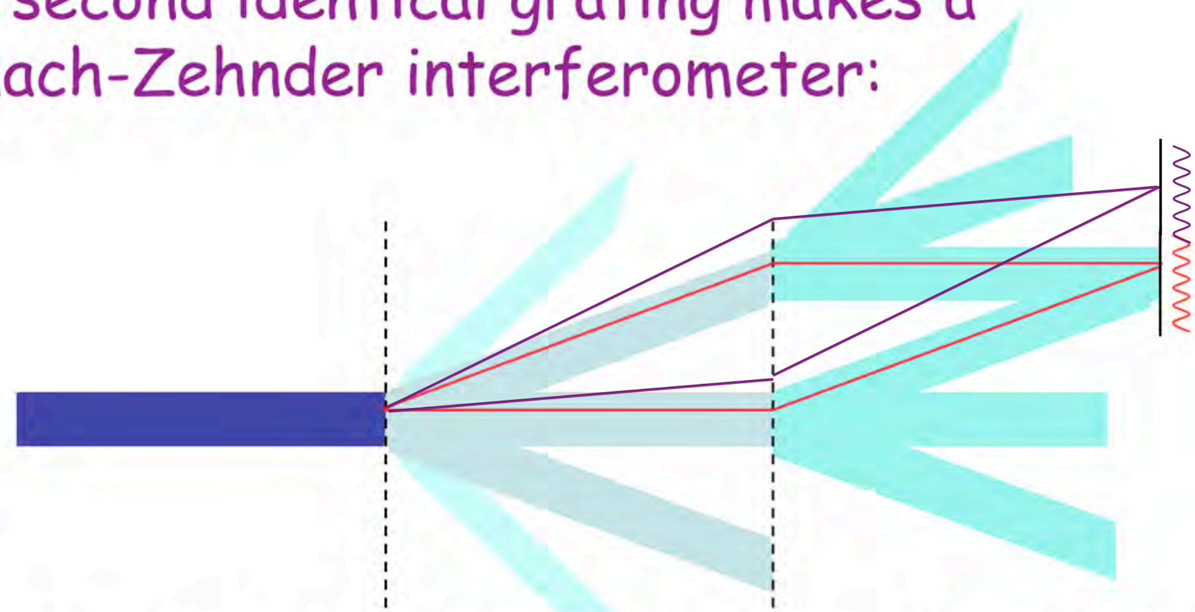

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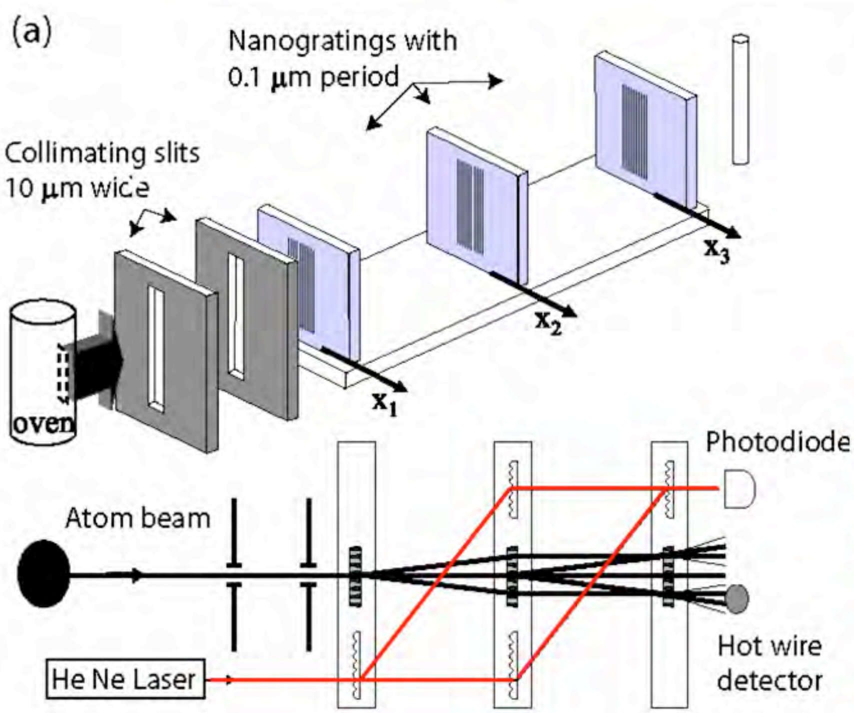
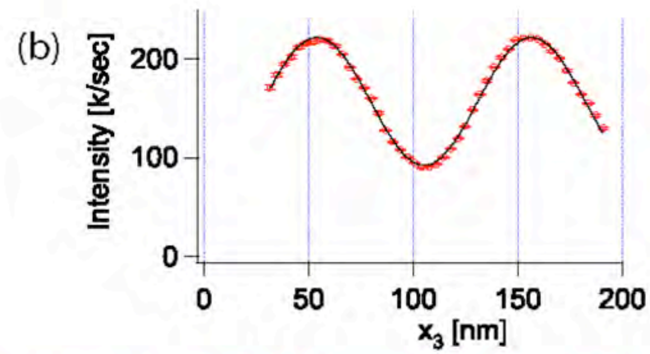
Atomic Interferometry Works!

Interference has been observed with the MIT/Arizona interferometer using an atomic Sodium beam



An atomic interferometer using sodium atoms and vacuum transmission gratings



This resolution is an order of magnitude better than we need for the antimatter gravity experiment. If this interferometer were rotated 90°, gravity would cause a phase shift of 200 radians. Atom interferometers (using lasers rather than gratings) have measured g to 1:10^{10}

Prototype Interferometer (Hydrogen)

R&D in Progress

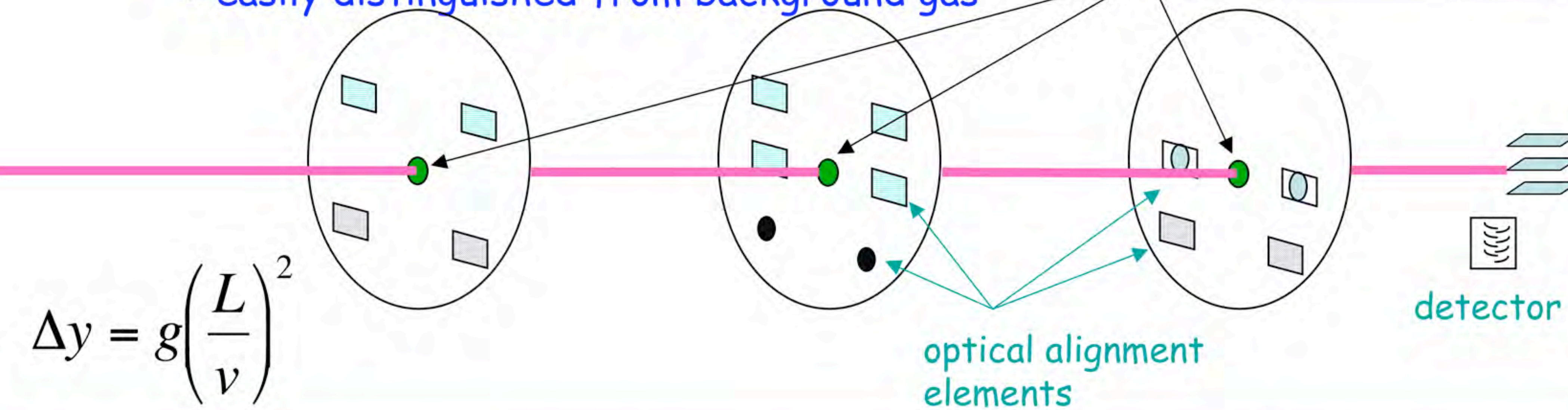
Transmission gratings have a 1 μm period

- ➢Courtesy of Max Planck Institute for Extraterrestrial Physics

L = 62 cm between pairs of gratings

Uses a metastable H beam

- ➢easily distinguished from background gas



$$\Delta y = g\left(\frac{L}{v}\right)^2$$

gravitational deflections: Δy=3.8 μm for v=1000 m/s => $\Delta\phi$=7.5 π radians
Δy=0.4 μm for v=3000 m/s => $\Delta\phi$=0.8 π radians
Δy=0.15 μm for v=5000 m/s => $\Delta\phi$=0.3 π radians

Antiprotons

Antiprotons are made at Fermilab and CERN

- CERN's AD cannot accumulate antiprotons
  - pulses of 3×10^7 antiprotons every 90 s
  - only runs part of year; future schedule uncertain
  - 10^{-3} capture efficiency (3×10^4 per pulse)
- Fermilab can accumulate antiprotons
  - stacking rate typically exceeds 2×10^{11}/hour
  - runs year-round
  - ~50% capture efficiency with deceleration ring (10^{-4} with degrader)
    - 10^5 x higher potential trapping rate than CERN
  - accumulating really helps!
    - antihydrogen production not tied to 90 sec. cycle
    - $\overline{H}$ from charge exchange goes as $(\overline{p}$ density$)^2$

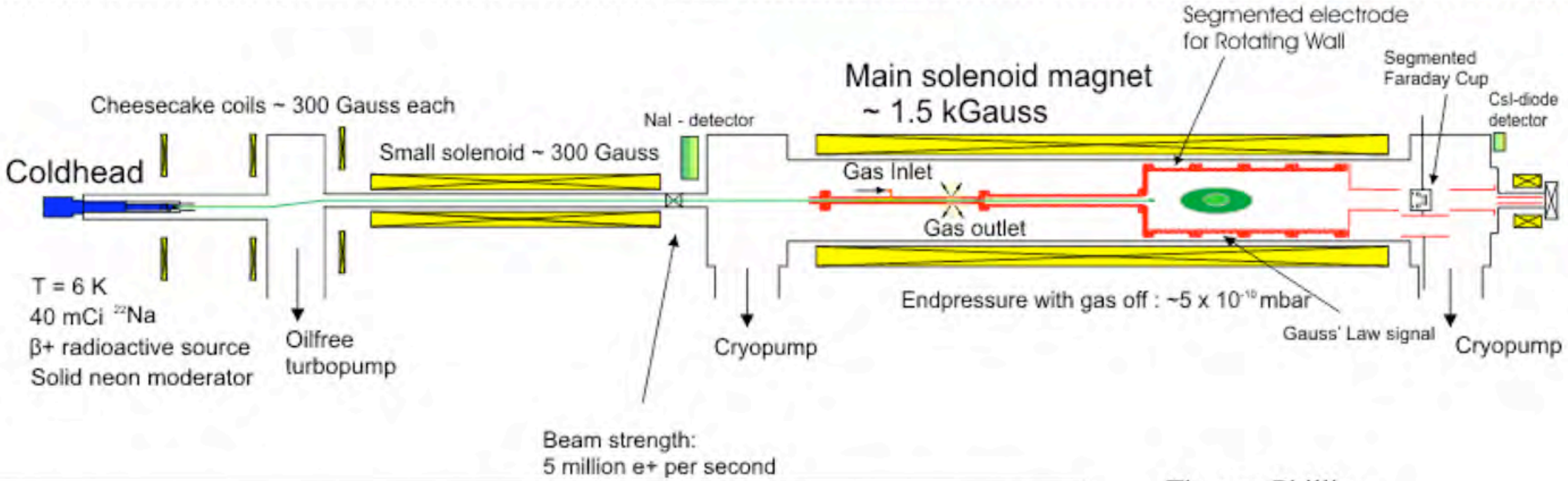
Bottom line: **Much easier to do the expt. at Fermilab.**

Much higher statistics possible at Fermilab.

Positron Source

Commercial solution is available

- up to 10^7 e^+/sec
- user supplies ^{22}Na
  - up to 150 mCi
- 5-11 month delivery
- \$212k + ^{22}Na source



ATHENA's positron accumulator (based upon same principle)

Antihydrogen Production

Antihydrogen Production

- Mechanisms:
  - 3-body: $\bar{p} + e^+ + e^+ \to \bar{H} + e^+$
  - radiative (re)combination $\bar{p} + e^+ \to \bar{H}$ + photon
  - 3-body $\bar{p} + \bar{p} + e^+ \to \bar{H} + \bar{p}$

- Rate estimate for first mechanism:

$$\Gamma = 6\times10^{-13}\left(\frac{4.2}{T}\right)^{\frac{9}{2}} n_e^2\left[s^{-1}\right]$$

(Glinsky & O'Neil Phys. Fluids **B3** (1991) 1279.)

T in K

n_e in cm^{-3}

For $n_e \geq 10^8/cm^3$ production rates ~ 45% of $\bar{p}$ converted to $\bar{H}$ per pass through a 10 cm positron plasma at 1 km/s

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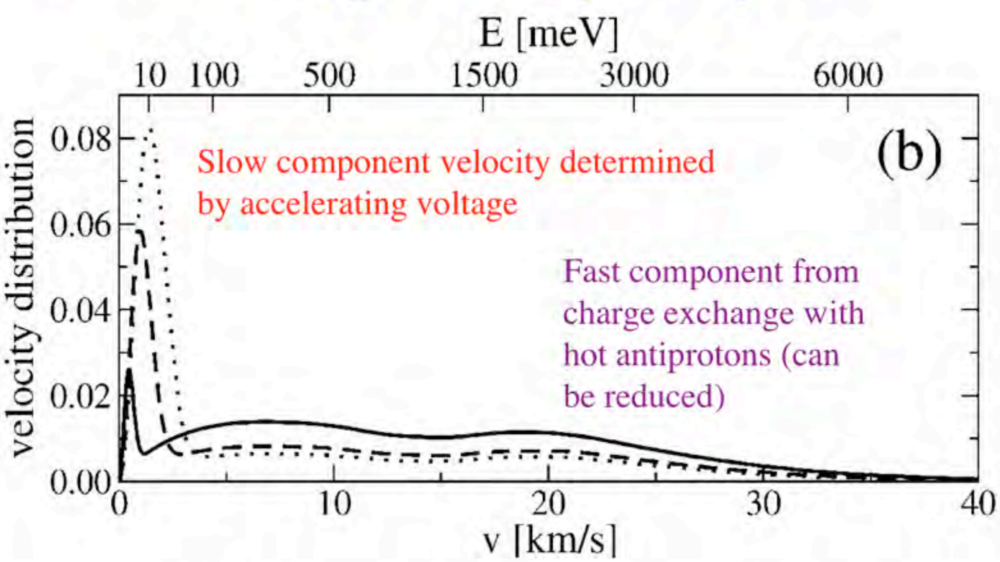
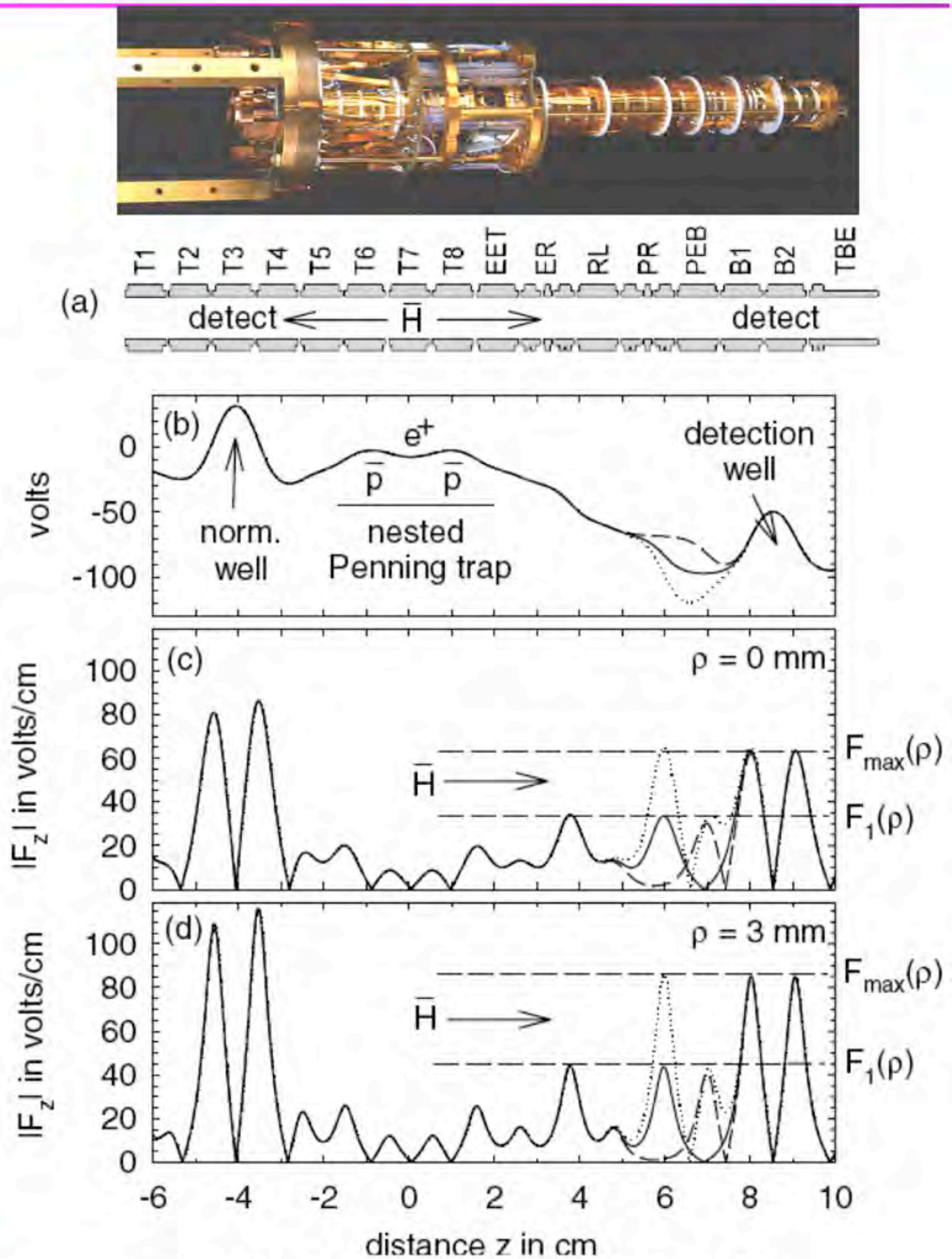
Antihydrogen Beam Proof-of-Principle

The ATRAP group has made antihydrogen in a beam with a velocity distribution nearly ideal for the gravity expt.



from Phys. Rev. Lett. 97, 143401 (2006)

Beam would need to be gated to get TOF



from Phys. Rev. Lett. 93, 073401 (2004)

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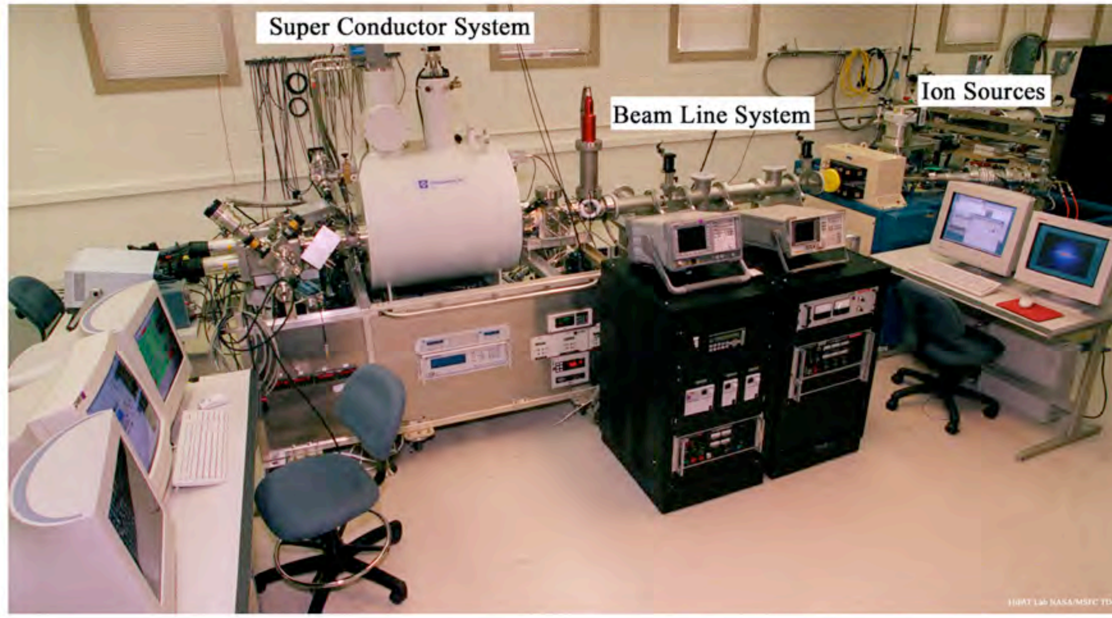
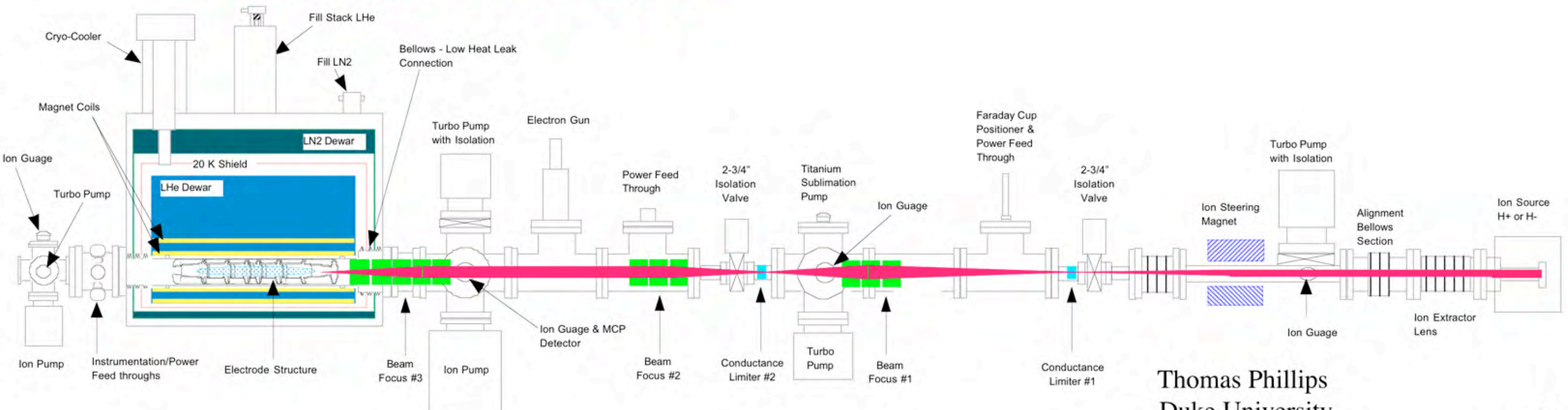
High Performance Antiproton Trap

We will use NASA's HiPAT to make $\bar{H}$

- 4T solenoid
- designed for 10^{12} $\bar{p}$
- H^+, H^- beams
- being crated for shipment here
- will need a new electrode structure



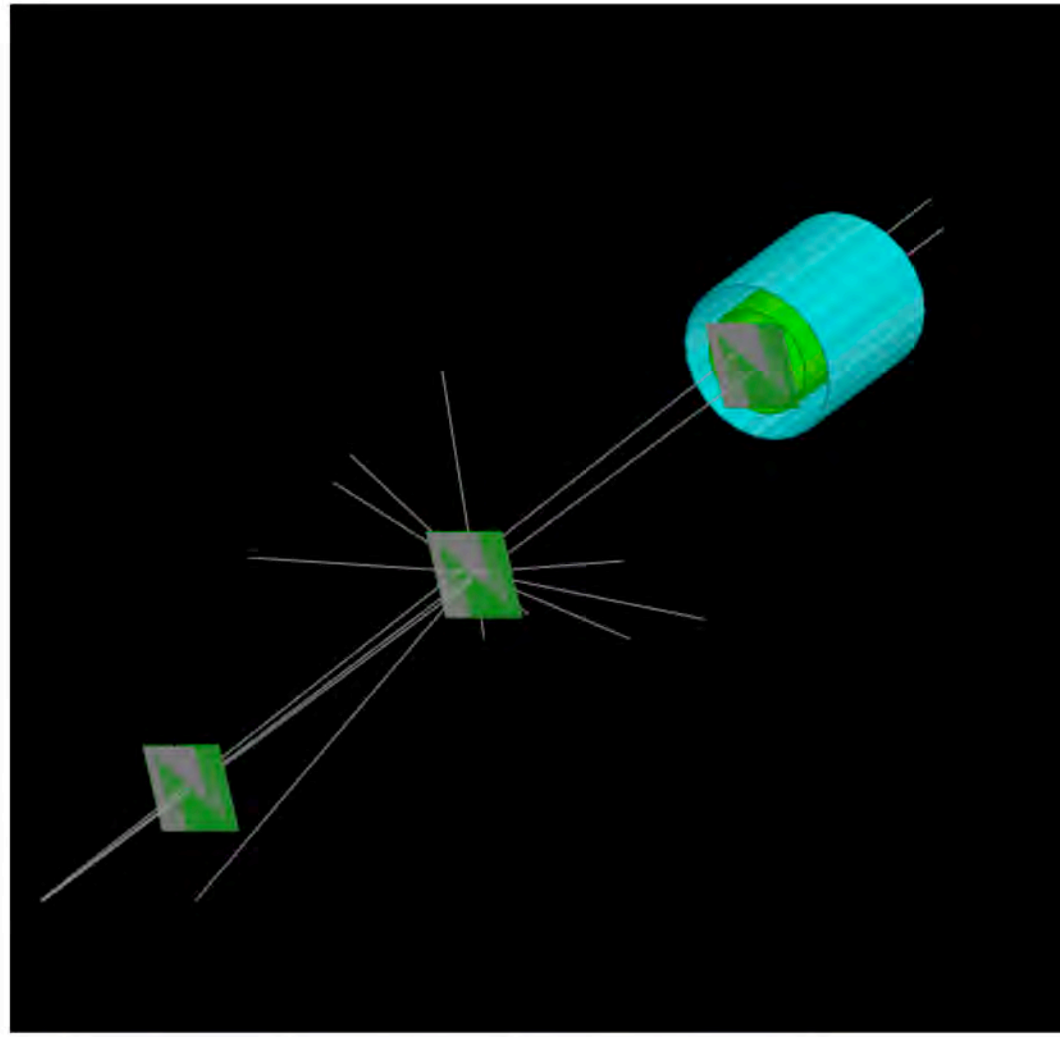


Antihydrogen Detection

Our baseline anti-hydrogen detector is position-sensitive MCP.

- also sensitive to metastable matter

In addition, a pair of scintillating-fiber barrels surrounding the region between the 3rd grating and the annihilator will identify annihilations on the 3rd grating.



Geant4 simulation of antihydrogen annihilation